Technical Manual

CulvertCalc™ IA
LRFD Software for Box Culverts

Automated RCB culvert analysis and design in accordance with the AASHTO LRFD Bridge Design Specifications, 5th Edition

Developed For:

Iowa Department of Transportation

Developed By:

Foth

Foth Infrastructure & Environment, LLC

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1 Definitions

Slab – The top horizontal member of the culvert

Floor – The bottom horizontal member of the culvert

Integral Wearing Surface – The sacrificial thickness on the top surface of the slab (intended for situations where the top surface of the slab serves as the roadway surface)

Mud Mat – The sacrificial thickness on the bottom surface of the floor

2 Abbreviations

AASHTO – American Association of State Highway and Transportation Officials

Iowa DOT – Iowa Department of Transportation

LRFD – Load and Resistance Factor Design

OBS – Office of Bridges and Structures

MCFT – Modified Compression Field Theory

RCB – Reinforced Concrete Box

3 Introduction

CulvertCalc was developed for the Iowa DOT to automate the analysis and design of RCB culverts. The Microsoft Windows-based program was written to conform to the AASHTO LRFD Bridge Design Specifications, 5th Edition, with Interims through 2010, and Iowa DOT policies. All specification articles, tables, and equations referenced within this manual, unless otherwise noted, are taken from the LRFD Bridge Design Specifications. Intended users for the program are professional engineers and technicians with a working knowledge of the LRFD Specifications and RCB culvert design.

CulvertCalc will analyze and design single, twin and triple barrel RCB culverts with user-specified cell span and height dimensions. Various input screens allow the user to select and/or adjust a variety of variables used in the analysis and design of a culvert such as live load properties, fill properties, load factors and material properties. By default, these variables are set to conform to the Iowa DOT policies used to design the RCB Culvert Standards. These default settings allow the user to analyze and design a standard culvert with a minimal amount of input. A customizable truck library allows the user to create custom trucks and save the library for future use.

CulvertCalc will automatically design a RCB culvert and provide a tabular output of the required member thicknesses and various reinforcing properties as well as short- and long-format design reports. CulvertCalc will also check a design for compliance to applicable code provisions using member thicknesses and reinforcing properties entered by the user and provide an on-screen summary of non-compliant components, as well as short- and long-format reports that can be printed or saved for documentation purposes.

4 Units

The internal units used by the CulvertCalc are:

- Length – Inch
- Force – Kip

5 Sign Convention

A sign convention is necessary to interpret the direction of section forces presented in the CulvertCalc output. In general, the x-axis is aligned with the centerline of the floor and is considered positive in the right hand direction. The y-axis is aligned with the centerline of the left exterior wall and is considered positive in the upward direction. Section forces for each element in the RCB culvert are provided at the tenth points along the length of the element.

5.1 Slab and Floor

Section numbers increase from left to right along the length of the member. Positive moments induce tension stress on the bottom face of the member. Positive shear forces act up on the left side of section and down on the right side of section. Tensile axial forces are considered as positive forces. The directions of positive internal forces are shown in Figure 5.1-1.

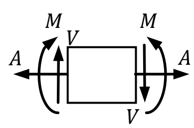


Figure 5.1-1 Sign Convention for Positive Internal Forces in Slab and Floor

5.2 Walls

Section numbers increase from top to bottom along the length of the member. Positive moments induce tension stress on the left face of the member. Positive shear forces act right on the top side of section and left on the bottom side of section. Tensile axial forces are considered as positive forces. The directions of positive internal forces are shown in Figure 5.2-1.

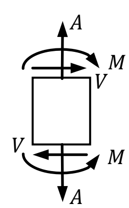


Figure 5.2-1 Sign Convention for Positive Internal Forces in Walls

6 Section Properties

All structural analysis and capacity calculations are based on a 12 in. long barrel section. For the slab, the structural section thickness is taken as the overall slab thickness minus the integral wearing surface thickness. For the floor, the structural section thickness is taken as the overall floor thickness minus the mud mat thickness. For both the interior and exterior walls, the structural section thickness is the respective overall wall thickness. Stick elements for the structural analysis process are established at the mid-thickness of the structural section. The cross-sectional area and moment of inertia of each member is calculated using the structural section thickness and the 12 in. strip width.

7 Component Loads

7.1 Dead Load of Structural Components (DC)

Self-weight of the slab is modeled as a transverse distributed load acting in the negative y-direction along the full length of the slab element(s). Magnitude of the distributed load is the product of the overall slab thickness, 12 in., and the user-specified structural concrete unit weight.

Self-weight of the walls is modeled as an axial distributed load acting in the negative y-direction along the full length of each wall element. Magnitude of the distributed load is the product of the respective wall thickness, 12 in., and the user-specified structural concrete unit weight.

Self-weight of the floor is directly resisted by the soil and not included in the analysis. The floor however resists an assumed uniform soil pressure due to the self-weight of the slab, walls, haunch, and frost trough. The magnitude of the soil pressure is the product of the cross-sectional area of the culvert above the top of the floor, 12 in., and the user-specified structural concrete unit weight divided by the overall width of the floor. This distributed transverse load acts along the full length of the floor element(s) in the positive y-direction.

7.2 Dead Load of Wearing Surfaces (DW)

Self-weight of the pavement is modeled as a surcharge load. Magnitude of the surcharge load is the product of the pavement thickness, 12 in., and the user-specified pavement unit weight. This surcharge load is applied to the full length of the slab element(s) as a distributed transverse load acting in the negative y-direction.

The surcharge load induces a horizontal soil pressure on the exterior walls. Magnitude of the soil pressure is the product of the surcharge load and the at-rest lateral earth pressure coefficient. The at-rest lateral earth pressure coefficient is calculated per AASHTO LRFD Eq. 3.11.5.2-1 using the user-specified angle of internal friction of the soil. The soil pressure is applied as a transverse distributed load along the length of the exterior wall elements acting in the positive x-direction for the left wall and the negative x-direction for the right wall.

The floor resists an assumed uniform soil pressure due to the surcharge load acting on the slab. The soil pressure magnitude is the product of the distributed surcharge load and the overall slab width divided by the overall floor width. This distributed transverse load is applied to the full length of the floor element(s) acting in the positive y-direction.

7.3 Vertical Pressure from Dead Load of Earth Fill (EV)

Vertical earth pressure acting on the slab is modeled as a uniform transverse distributed load acting along the full length of the slab element(s). Magnitude of the distributed load is the product of the fill depth less the pavement thickness, 12 in., user-specified soil unit weight, and the soil-structure interaction factor. For an embankment installation condition, the soil-structure interaction factor is calculated per AASHTO LRFD Eq. 12.11.2.2.1-1. The upper limit for the calculated soil-structure interaction factor is based on the user-specified backfill compaction condition per AASHTO LRFD Art. 12.11.2.2. For a trench installation condition, the user-specified soil-structure interaction factor is used in the distributed load calculation.

The floor resists an assumed uniform soil pressure due to the vertical earth pressure acting on the slab. The soil pressure magnitude is the product of the distributed load acting on the slab and the overall slab width divided by the overall floor width. This distributed transverse load is applied to the full length of the floor element(s) acting in the positive y-direction.

7.4 Horizontal Earth Pressure Load (EH)

Horizontal earth pressure acting on the exterior walls is modeled as a linearly varying transverse distributed load. At the top of the exterior wall elements, the distributed load magnitude is the product of the vertical distance from the bottom of the pavement to the mid-depth of the slab structural depth, 12 in., user-specified soil unit weight, and the at-rest lateral earth pressure coefficient. The at-rest lateral earth pressure coefficient is calculated per AASHTO LRFD Eq. 3.11.5.2-1 using the user-specified angle of internal friction of the soil. At the bottom of the exterior wall elements, the distributed load magnitude is the product of the vertical distance from the bottom of the pavement to the mid-depth of the floor structural depth, 12 in., user-specified soil unit weight, and the at-rest lateral earth pressure coefficient. The linearly varying distributed load acts in the positive x-direction for the left exterior wall and the negative x-direction for the right exterior wall.

7.5 Water Load (WA)

Horizontal pressure due to water within the culvert is modeled as a linearly varying transverse distributed load applied to the exterior walls. Limits of the distributed load on the exterior walls are the horizontal projection of the underside of the slab and the horizontal projection of the top of floor. Magnitude of the distributed load near top of the wall is the product of the user-specified vertical distance between the water surface and the bottom of the slab, 12 in., and the user-specified water unit weight. Magnitude of the distributed load near the bottom of the wall is the product of the user-specified distance between the water surface and the bottom of the slab increased by the cell height and frost trough depth, 12 in., and the user-specified water unit weight. The linearly varying distributed load acts in the negative x-direction for the left exterior wall and the positive x-direction for the right exterior wall.

7.6 Live Load Surcharge (LS)

Horizontal pressure due to live load surcharge is modeled as a uniform transverse distributed load applied to the exterior walls. An equivalent height of soil is interpolated from AASHTO LRFD Table 3.11.6.4-1 with the “Abutment Height” taken as the distance from the pavement surface to the bottom of the floor. The magnitude of the distributed load is then calculated per AASHTO LRFD Eq. 3.11.6.4.1 and is the product of the equivalent height of soil, 12 in., the user-specified soil unit weight, and the at-rest lateral earth pressure coefficient. The at-rest lateral earth pressure coefficient is calculated per AASHTO LRFD Eq. 3.11.5.2-1 using the user-specified angle of internal friction of the soil. The uniform distributed load acts in the positive x-direction for the left exterior wall and the negative x-direction for the right exterior wall.

7.7 *Vehicular Live Load (LL)*

Axle loads for live load vehicles are distributed differently depending on the fill depth and user-specified options. In general, axle loads are either modeled as concentrated transverse loads or distributed transverse loads. When the fill depth is 2.0 ft. or greater, axle loads will always be modeled as distributed transverse loads. For fill depths less than 2.0 ft., axle loads will be modeled as concentrated transverse loads unless the *Distribute Axle Loads Parallel to Span for Fill Heights < 2 ft* checkbox in the *Live Load* screen (Figure 7.7-1) is checked by the user, in which case the axle loads will then be modeled as distributed transverse loads.

To model axle loads as concentrated transverse loads, an equivalent distribution length perpendicular to the span is first calculated per AASHTO LRFD Eq. 4.6.2.10.2-1 with the clear span being taken as the cell width. The magnitude of the concentrated transverse load for each axle is then the product of the axle load, the single lane multiple presence factor, and 12 in. divided by the equivalent distribution length perpendicular to the span. The single lane multiple presence factor is specified in AASHTO LRFD Table 3.6.1.1.2-1.

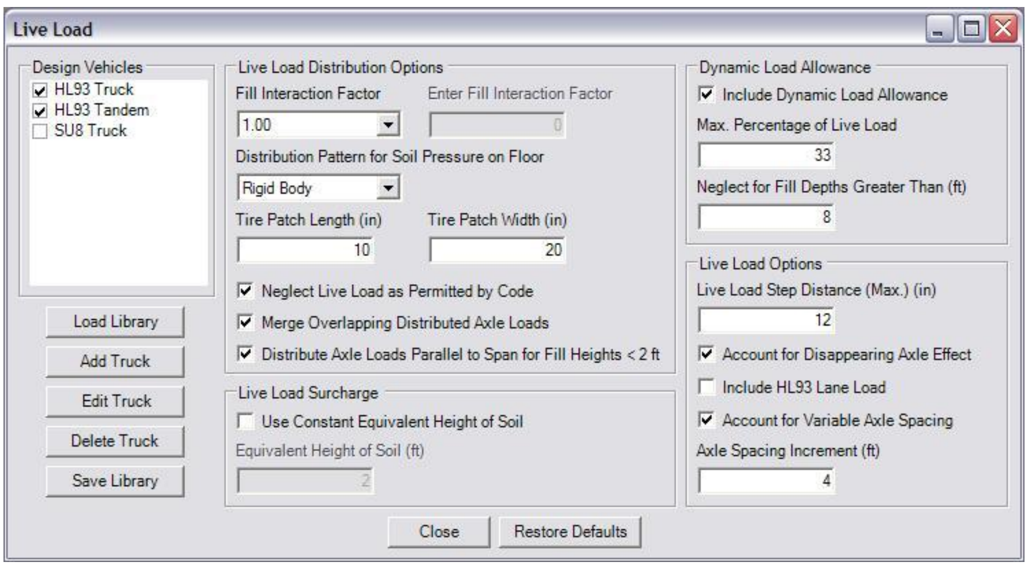


Figure 7.7-1 Live Load Screen

When axle loads are modeled as distributed transverse loads for fill heights less than 2.0 ft., a concentrated transverse load is first calculated as described in the previous paragraph. The equivalent distribution length parallel to the span is then calculated per AASHTO LRFD Eq. 4.6.2.10.2-2 using the user-specified tire contact patch length and fill interaction factor. The distributed transverse load magnitude for each axle is then taken as the quotient of the concentrated transverse load for that axle and the equivalent distribution length parallel to the span.

For fill depths 2.0 ft. or greater, axle loads are uniformly distributed over a rectangular area per AASHTO LRFD Art. 3.6.1.2.6 using the user-specified tire contact patch length and width, and fill interaction factor. Distributed load magnitudes for one-, two-, and three-lanes loaded scenarios are calculated considering multiple presence factors from AASHTO LRFD Table

3.6.1.1.2-1, and the scenario producing the greatest distributed pressure is used in the live load analysis. The magnitude of the uniform distributed transverse load for each axle is taken as the distributed pressure acting on a 12 in. wide strip and limits of the uniform distributed transverse load are based on the width of the distributed pressure in the direction parallel to the span.

When the limits of distributed transverse loads from adjacent axles overlap, the individual overlapping distributed transverse loads will be combined into one single uniform distributed transverse load if the *Merge Overlapping Distributed Axle Loads* option is selected on the *Live Load* screen (Figure 7.7-1). Calculation of the combined uniform distributed transverse load is presented in Figure 7.7-2.

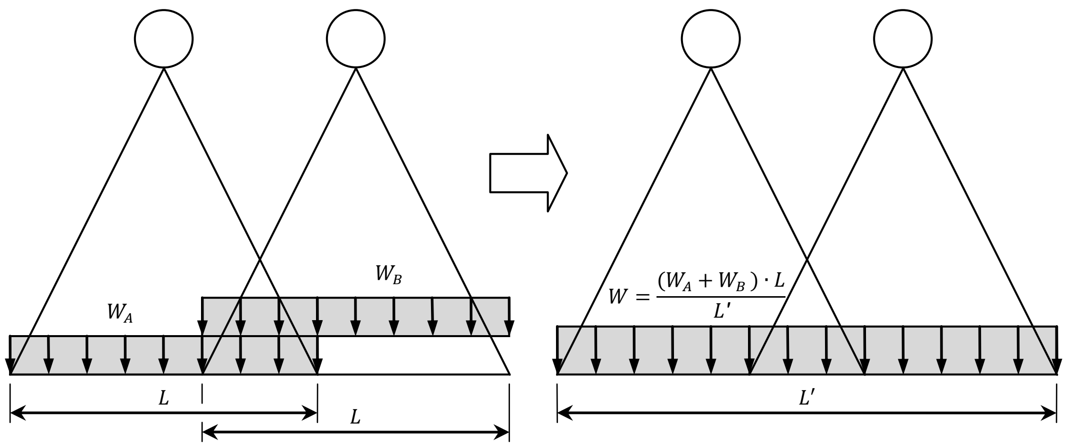
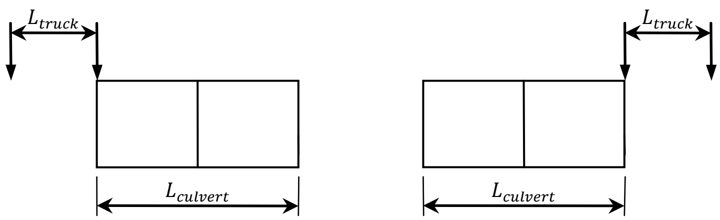


Figure 7.7-2 Merge Overlapping Distributed Axle Loads

Each live load vehicle is stepped across the RCB culvert from left to right in a series of successive positions to generate the live load section force envelopes. The maximum distance between successive positions is entered by the user in the *Live Load Step Distance (Max.)* textbox on the *Live Load* screen (Figure 7.7-1). Calculation of the actual distance between successive positions and the first and last vehicle positions are presented in Figure 7.7-3. The section force envelopes generated by stepping the vehicle left to right across the RCB culvert are mirrored about the vertical centerline of the RCB culvert to replicate stepping the vehicle from right to left. The maximum/minimum forces from the original and mirrored are then compared and the controlling forces are saved to the final live load envelope.

The HL93 truck, HL93 tandem, and SU8 truck are coded into CulvertCalc and cannot be modified by the user. The HL93 vehicles are defined in AASHTO LRFD Art. 3.6.1.2 and the SU8 truck is defined in <u>The Manual for Bridge Evaluation</u> Figure 6B.9.2-3. Axle loads and axle spacings for these vehicles are presented in Figure 7.7-4. Additional vehicles may be defined by the user with the *Truck Editor* (Figure 7.7-5). The HL93 vehicles are used in Strength I load combinations and the SU8 truck and any user-defined trucks are used in Strength II load combinations.

The rear axle spacing for the HL93 truck and the front axle spacing for the SU8 truck can vary between minimum and maximum values. The variable axle spacings are modeled as a series of successive runs with the variable axle spacing increasing by a user-specified increment between successive runs. The maximum axle spacing is limited by the overall width of the RCB culvert, measured between the centerlines of the exterior walls, since runs with axle spacings longer than these dimensions will not result in controlling maximum/minimum section forces.

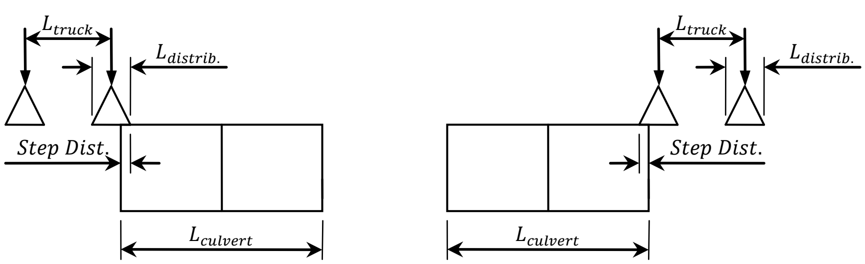


First Position Last Position

$$No.of\ Steps = \ Round\ Up\left(\frac{L_{truck} + L_{culvert}}{User\ Max.Step\ Distance}\right)$$

$$Step\ Distance = \frac{L_{truck} + L_{culvert}}{No.of\ Steps}$$

Axle Loads Modeled as Concentrated Transverse Loads



First Position Last Position

$$No.of\ Steps = \ Round\ Up\left(\frac{L_{truck} + L_{culvert} + L_{distrib.}}{User\ Max.Step\ Distance}\right) - 2$$

$$Step\ Distance = \frac{L_{truck} + L_{culvert} + L_{distrib.}}{No.of\ Steps + 2}$$

Axle Loads Modeled as Distributed Transverse Loads

Figure 7.7-3 First and Last Live Load Positions

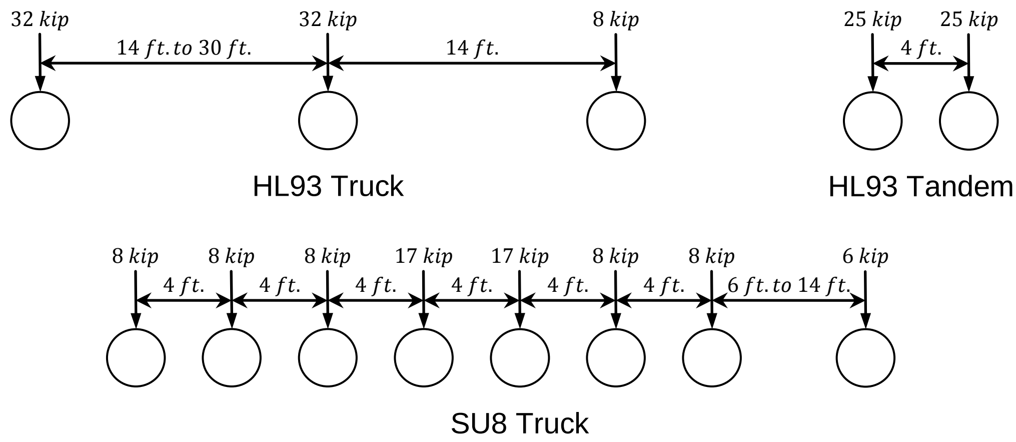


Figure 7.7-4 Internal Live Load Vehicles

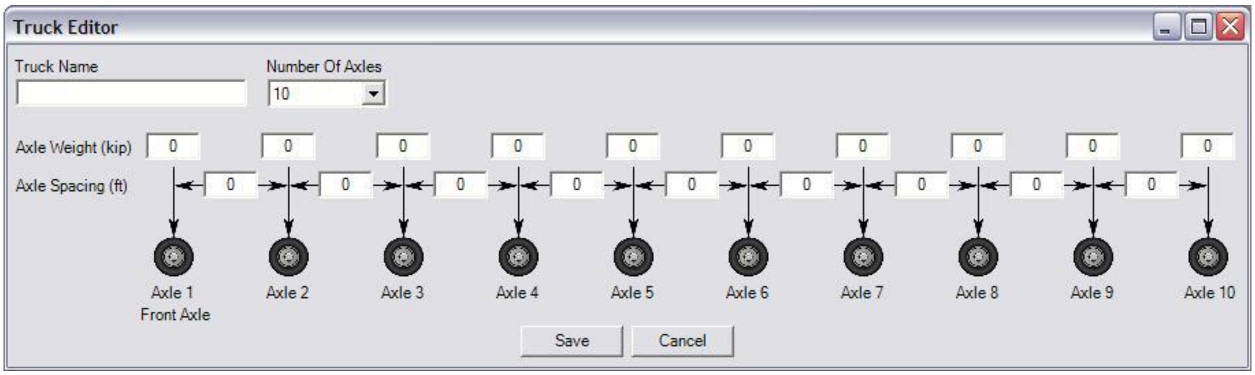
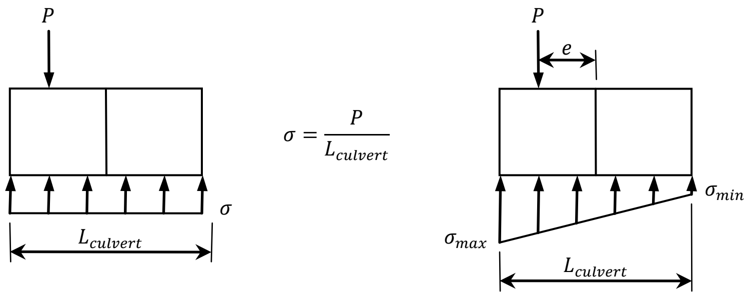


Figure 7.7-5 Truck Editor Screen

The HL93 lane load, as defined in AASHTO LRFD Art. 3.6.1.2.4, is not typically included with the live load vehicles in RCB culvert design. However, if so desired by the user, the HL93 lane load may be included in the analysis by checking the *Include HL93 Lane Load* checkbox on the *Live Load* screen (Figure 7.7-1). The lane load is distributed perpendicular to the span using the fill interaction factor and is considered limitless in the direction parallel to the span. Pattern loading of the individual barrel spans for twin and triple barrel configurations is performed to maximize/minimize the section forces.

Soil pressure acting on the floor due to live load is modeled as either a uniform distributed transverse force or a linearly varying distributed transverse force (rigid body) based on the user selection in the Distribution *Pattern for Soil Pressure on Floor* combo box on the *Live Load* screen (Figure 7.7-1). Calculation of the two soil pressure distribution patterns is presented in Figure 7.7-6. For the rigid body soil distribution case, the supporting soil below the culvert is assumed to be in tension when the eccentricity (e) exceeds one-sixth of the culvert width ($L_{culvert}$).



$$\sigma = \frac{P}{L_{culvert}}$$

$$\sigma_{max} = \frac{P}{L_{culvert}} + \frac{P \cdot e}{\frac{1}{6} \cdot L_{culvert}^{2}}$$

$$\sigma_{min} = \frac{P}{L_{culvert}} - \frac{P \cdot e}{\frac{1}{6} \cdot L_{culvert}^{2}}$$

Uniform Soil Pressure Distribution

Rigid Body Soil Pressure Distribution

Figure 7.7-6 Live Load Soil Pressure Distribution

7.8 Vehicular Dynamic Load Allowance (IM)

Dynamic live load allowance is accounted for as a percentage of the live load force effects. The IM percentage is dependent upon fill depth and user-specified input on the *Live Load* screen (Figure 7.7-1). The default settings for IM are based on AASHTO LRFD Eq. 3.6.2.2-1 where the maximum IM percentage, which occurs when there is no fill over the RCB culvert, is 33% and the IM percentage lineally decreases to 0% when the fill depth is 8 ft. The IM percentage is only applied to vehicles; it is not applied to the HL93 lane load.

8 Load Cases

Load cases are used to maximize force effects on various elements in the RCB culvert. The following three load cases are used by CulvertCalc:

1. Case A – Maximize Vertical Forces / Minimize Horizontal Forces
   In Case A, vertical forces are maximized by applying maximum load factors to DC, DW, and EV and including LL+IM. Inward acting horizontal forces are minimized by applying the 0.5 factor to EH as specified in AASHTO LRFD Art. 3.11.7, including WA and neglecting LS. The minimum load factor is applied to EH.
2. Case B – Minimize Vertical Forces / Maximize Horizontal Forces
   In Case B, horizontal forces are maximized by applying the maximum load factor to EH, including LS and neglecting WA. Vertical forces are minimized by applying minimum load factors to DC, DW, and EV and neglecting LL+IM.
3. Case C – Maximize Vertical Forces / Maximize Horizontal Forces
   In Case C, maximum load factors are applied to DC, DW, EV, and EH and only WA is neglected.

9 Load Combinations

Load combinations are assembled according to AASHTO LRFD Table 3.4.1-1 to determine both Strength- and Service-level design forces. Default load factors used by these combinations adhere to AASHTO LRFD Table 3.4.1-1 and AASHTO LRFD Table 3.4.1-2. Default load modifiers used by these combinations adhere to Articles 1.3.3, 1.3.4, and 1.3.5. Load factors and load modifiers may be changed by the user on the *Load Factors, Load Modifiers and Exposure Factors* screen. The load combinations used by CulvertCalc are presented as follows:

- Strength I & Strength II
  - Case A
    $Q = \eta_{DC(max.)} \cdot \gamma_{DC(max.)} \cdot DC + \eta_{DW(max.)} \cdot \gamma_{DW(max.)} \cdot DW + \eta_{EV(max.)} \cdot \gamma_{EV(max.)} \cdot EV + 0.5 \cdot \eta_{EH(min.)} \cdot \gamma_{EH(min.)} \cdot EH + \eta_{LL+IM} \cdot \gamma_{LL+IM} \cdot (LL + IM) + \eta_{WA} \cdot \gamma_{WA} \cdot WA + 0 \cdot LS$
  - Case B
    $Q = \eta_{DC(min.)} \cdot \gamma_{DC(min.)} \cdot DC + \eta_{DW(min.)} \cdot \gamma_{DW(min.)} \cdot DW + \eta_{EV(min.)} \cdot \gamma_{EV(min.)} \cdot EV + \eta_{EH(max.)} \cdot \gamma_{EH(max.)} \cdot EH + 0 \cdot (LL + IM) + 0 \cdot WA + \eta_{LS} \cdot \gamma_{LS} \cdot LS$
  - Case C
    $Q = \eta_{DC(max.)} \cdot \gamma_{DC(max.)} \cdot DC + \eta_{DW(max.)} \cdot \gamma_{DW(max.)} \cdot DW + \eta_{EV(max.)} \cdot \gamma_{EV(max.)} \cdot EV + \eta_{EH(max.)} \cdot \gamma_{EH(max.)} \cdot EH + \eta_{LL+IM} \cdot \gamma_{LL+IM} \cdot (LL + IM) + 0 \cdot WA + \eta_{LS} \cdot \gamma_{LS} \cdot LS$

- Service I
  - Case A
    $Q = \gamma_{DC} \cdot DC + \gamma_{DW} \cdot DW + \gamma_{EV} \cdot EV + 0.5 \cdot \gamma_{EH} \cdot EH + \gamma_{LL+IM} \cdot (LL + IM) + \gamma_{WA} \cdot WA + 0 \cdot LS$
  - Case B
    $Q = \gamma_{DC} \cdot DC + \gamma_{DW} \cdot DW + \gamma_{EV} \cdot EV + \gamma_{EH} \cdot EH + 0 \cdot (LL + IM) + 0 \cdot WA + \gamma_{LS} \cdot LS$
  - Case C
    $Q = \gamma_{DC} \cdot DC + \gamma_{DW} \cdot DW + \gamma_{EV} \cdot EV + \gamma_{EH} \cdot EH + \gamma_{LL+IM} \cdot (LL + IM) + 0 \cdot WA + \gamma_{LS} \cdot LS$

For the Strength I and Service I load combinations, the live load is taken as the section force envelope for the HL93 truck, HL93 tandem, and HL93 lane loads. For the Strength II load combination, the live load is taken as the section force for the SU8 truck and any user defined vehicles.

10 RCB Culvert Design

10.1 General

CulvertCalc begins the reinforced concrete design process once the section force envelopes are calculated for the Strength- and Service-level load combinations. As presented in Figure 10.1-1, the general design process is iterative starting with user-specified member thicknesses and increasing member thicknesses as needed to satisfy design requirements. A maximum member thickness limit is applied to prevent an infinite loop that may arise when design criteria require relatively thick walls and reinforcing limitations cannot satisfy minimum reinforcing requirements. The component loads and force distribution within the culvert are a function of the member thicknesses and thus the structural model must be solved at the start of each iteration. If multiple fill heights are specified by the user, the process presented in Figure 10.1-1 is repeated for each fill height.

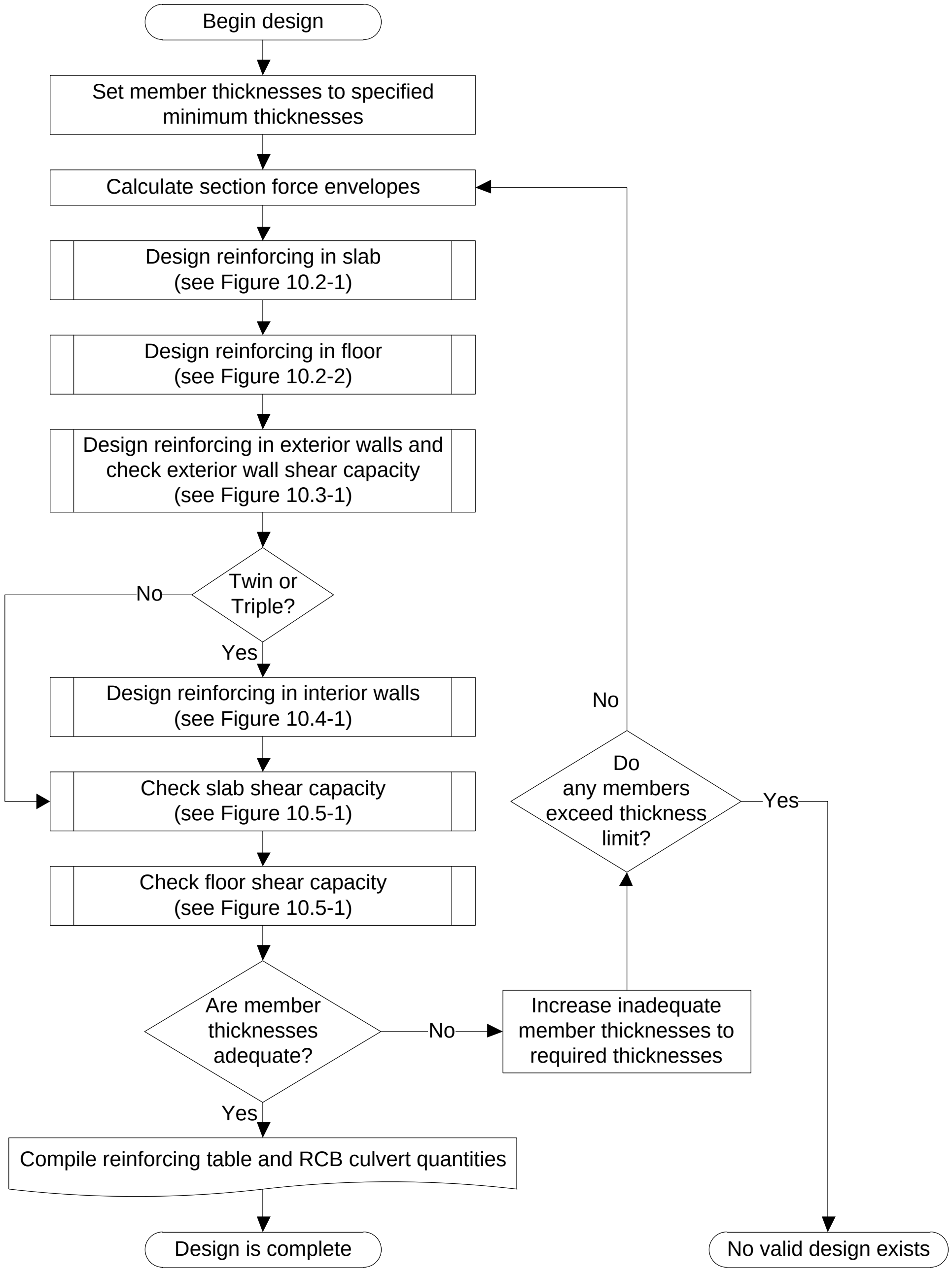


Figure 10.1-1 General Flowchart

Reinforcing patterns in the slab and floor follow the Iowa DOT RCB culvert standards. Descriptions of bar designations used by CulvertCalc are presented in Table 10.1-1 and Table 10.1-2.

The process of selecting a bar size and spacing combination for a particular element starts by determining the reinforcing area required to satisfy Strength requirements and if applicable, shrinkage and temperature requirements. CulvertCalc then selects the least-weight bar size and spacing combination that satisfies this required area of steel. Crack control provisions, per AASHTO LRFD Art. 5.7.3.4, are then evaluated for this bar size and spacing combination. If crack control provisions are not satisfied, these provisions are evaluated for the next least-weight bar size and spacing combination. This process repeats until an acceptable bar size and spacing combination is reached or it is determined none of the available bar size and spacing combinations satisfy these provisions, at which point the member thickness is increased. Available bar size and spacing combinations in order of increased reinforcing area are presented in Table 10.1-3, Table 10.1-4, and Table 10.1-5. Bar spacings are set so bar patterns will always repeat in three feet intervals.

Table 10.1-1 Bar Designations for Single Barrel Configuration

Designation	Location
a1	Vertical bar on inside face of exterior walls.
b1	Longitudinal bar on both faces of exterior walls.
e1	Longitudinal bar in the bottom of the slab.
e2	Longitudinal bar in the top of the slab.
f1	Longitudinal bar in top of the floor.
f2	Longitudinal bar in bottom of the floor.
k1	Full width transverse bar in the bottom of the slab.
k2	Transverse corner bar extending from the outside face of the exterior wall to the top of the slab.
k9	Full width transverse bar in the top of the slab located at the barrel segment ends.
m1	Full width transverse bar in the top of the floor.
m2	Transverse corner bar extending from the outside face of the exterior wall to the bottom of the floor.
m9	Full width transverse bar in the bottom of the floor located at the barrel segment ends.

Table 10.1-2 Bar Designations for Twin and Triple Barrel Configurations

Designation	Location
a1	Vertical bar on inside face of exterior walls.
a2	Vertical bar on both faces of interior walls.
b1	Longitudinal bar on both faces of exterior walls.
b2	Longitudinal bar on both faces of interior walls.
e1	Longitudinal bar in the bottom of the slab.
e2	Longitudinal bar in the top of the slab.
f1	Longitudinal bar in top of the floor.
f2	Longitudinal bar in bottom of the floor.
k1	Full width transverse bar in the bottom of the slab.
k2	Short transverse bar in the bottom of the slab that alternates with the k1 bars. Located in the exterior spans for the triple barrel configuration.
k3	Short transverse bar in the bottom of the slab that alternates with the k1 bars for the triple barrel configuration. Located in the interior span.
k4	Transverse corner bar extending from the outside face of the exterior wall to the top of the slab.
k6	Full width transverse bar in top of the slab for twin and triple barrel configurations.
k7	Short transverse bar in the top of the slab that alternates with the k6 bars for twin and triple barrel configurations. Located over the interior walls.
k9	Full width transverse bar in the top of the slab located at the barrel segment ends.
m1	Full width transverse bar in the top of the floor.
m2	Short transverse bar in the top of the floor that alternates with the m1 bars. Located in the exterior spans for the triple barrel configuration.
m3	Short transverse bar in the top of the slab that alternates with the m1 bars for the triple barrel configuration. Located in the interior span.
m4	Transverse corner bar extending from the outside face of the exterior wall to the bottom of the floor.
m6	Full width transverse bar in bottom of the floor for twin and triple barrel configurations.
m7	Short transverse bar in the bottom of the floor that alternates with the m6 bars for twin and triple barrel configurations. Located under the interior walls.
m9	Full width transverse bar in the bottom of the floor located at the barrel segment ends.

Table 10.1-3 Bar Size and Spacing Combinations for Non-Alternating Bars

Bar Size	Spacing (in)	A_s per ft (in^2)
4	12	0.2000
4	9	0.2667
5	12	0.3100
4	6	0.4000
5	9	0.4133
6	12	0.4400
6	9	0.5867
7	12	0.6000
5	6	0.6200
8	12	0.7900
7	9	0.8000
6	6	0.8800
9	12	1.0000
8	9	1.0533
7	6	1.2000
9	9	1.3333
8	6	1.5800
9	6	2.0000
10	6	2.5400
11	6	3.1200

Notes:

1. The above table excludes bars spaced 4.5 in. due to concerns related to the labor cost of placing closely spaced bars.
2. The Iowa DOT generally prefers to not use #10 and #11 bars in RCB culverts, however the above table includes #10 and #11 bars spaced at 6 in. for situations where nonstandard fills and/or nonstandard geometry require the use of larger diameter bars.
3. Bar size and spacing combinations from the above table apply to the following bars:
    - a1, k1, k2, m1, and m2 for single cell RCB culverts
    - a1, a2, k4, and m4 for twin and triple cell RCB culverts

Table 10.1-4 Bar Size and Spacing Combinations for Alternating Bars (One Size Maximum Difference)

Bar A Size	Bar B Size	Spacing (in)	As per ft (in^2)
4	4	9	0.2667
4	5	9	0.3400
4	4	6	0.4000
5	5	9	0.4133
5	6	9	0.5000
4	5	6	0.5100
4	4	4.5	0.5333
6	6	9	0.5867
5	5	6	0.6200
4	5	4.5	0.6800
6	7	9	0.6933
5	6	6	0.7500
7	7	9	0.8000
5	5	4.5	0.8267
6	6	6	0.8800
7	8	9	0.9267
5	6	4.5	1.0000
6	7	6	1.0400
8	8	9	1.0533
6	6	4.5	1.1733
8	9	9	1.1933
7	7	6	1.2000
9	9	9	1.3333
6	7	4.5	1.3867
7	8	6	1.3900
8	8	6	1.5800
7	7	4.5	1.6000
8	9	6	1.7900
7	8	4.5	1.8533
9	9	6	2.0000
8	8	4.5	2.1067
8	9	4.5	2.3867
9	9	4.5	2.6667
9	10	4.5	3.0267
10	10	4.5	3.3867
10	11	4.5	3.7733
11	11	4.5	4.1600

Notes:

1. The above table limits the difference between alternating bars to one size or less.

2. The Iowa DOT generally prefers to not use #10 and #11 bars in RCB culverts, however the above table lists combinations which include #10 and #11 bars for situations where nonstandard fills and/or nonstandard geometry require the use of larger diameter bars.
3. Bar size and spacing combinations from the above table apply to the following bars:
   - k1, k2, m1, and m2 for twin cell RCB culverts
   - k1, k2, k3, m1, m2, and m3 for triple cell RCB culverts

Table 10.1-5 Bar Size and Spacing Combinations for Alternating Bars (Three Sizes Maximum Difference)

Bar A Size	Bar B Size	Spacing (in)	As per ft (in^2)
4	4	9	0.2667
4	5	9	0.3400
4	4	6	0.4000
5	5	9	0.4133
4	6	9	0.4267
5	6	9	0.5000
4	5	6	0.5100
4	4	4.5	0.5333
4	7	9	0.5333
5	7	9	0.6067
5	5	6	0.6200
4	6	6	0.6400
4	5	4.5	0.6800
5	8	9	0.7333
5	6	6	0.7500
4	7	6	0.8000
5	5	4.5	0.8267
4	6	4.5	0.8533
5	7	6	0.9100
5	6	4.5	1.0000
4	7	4.5	1.0667
5	8	6	1.1000
5	7	4.5	1.2133
5	8	4.5	1.4667
6	8	4.5	1.6400
6	9	4.5	1.9200
7	10	4.5	2.4933
8	11	4.5	3.1333

Notes:

1. The above table limits the difference between alternating bars to three sizes or less.
2. Bar A was generally limited to a #4 or #5 however the two combinations at the bottom of the table utilize #6 bars to increase the available reinforcing area.

3. The Iowa DOT generally prefers to not use #10 and #11 bars in RCB culverts however the above table lists combinations which include #10 and #11 bars for situations where nonstandard fills and/or nonstandard geometry require the use of larger diameter bars.
4. Bar size and spacing combinations from the above table apply to the k6, k7, m6, and m7 for twin and triple cell RCB culverts.

The Auto Design function assumes a bar diameter for initial flexural strength calculations. For the slab and floor, a #9 bar is assumed. For the walls, a #8 bar is assumed. These assumptions lead to a conservative design for typical conditions. For design conditions that produce relatively thick members with bar sizes that exceed the aforementioned sizes, the Auto Design function may produce a marginally inadequate design. In these situations, it is recommended the Design Check function be used to verify the design produced by the Auto Design function.

10.2 Slab and Floor Design

The slab design process and floor design process are presented in Figure 10.2-1 and Figure 10.2-2, respectively, and a review of these flowcharts will reveal the two processes are nearly identical. One slight variation between the two processes is the critical section location for the shear capacity check when the *Vary Shear Critical Section Location in Slab with Fill Depth* checkbox on the *Analysis and Results* screen (Figure 10.2-3) is checked. When the fill depth is less than 2.0 ft., the shear critical section for the slab is taken at the end of the haunch based on the Iowa DOT OBS office practice. For fill depths equal to and greater than 2.0 ft., the shear critical section for the slab is taken at a distance d_v from the end of the haunch per AASHTO LRFD Art. C5.13.3.6.1. If the *Vary Shear Critical Section Location in Slab with Fill Depth* checkbox is not checked, the critical section location is taken at a distance d_v from the end of the haunch for all fill depths. The shear critical section location for the floor is always taken at a distance d_v from the end of the haunch, regardless of fill depth. The flexural critical section location for the slab and floor are located per AASHTO LRFD Art. C5.7.3.2.1.

The flexural reinforcing design process used for the slab and floor designs is presented in Figure 10.2-4. Within this process, a maximum reinforcing limit is set to ensure the section is classified as tension controlled as defined in AASHTO LRFD Art. 5.7.2.1. This limit is set at 63.4% of the balanced reinforcing ratio. The flexural reinforcing design process also includes checks to ensure the reinforcing satisfies the shrinkage and temperature reinforcing provisions of AASHTO LRFD Art. 5.10.8 for exposed surfaces, including the top of the slab for RCB culverts with no fill. Lastly, the flexural reinforcing design process includes checks to ensure the crack control provisions of AASHTO LRFD Art. 5.7.3.4 are satisfied. Axial force in the slab and floor at Service-level loads will typically be compressive except for shallow fill situations, where a small tensile force may be present under the Case B load combination. Accounting for the compressive force will result in a lower stress in tensile reinforcing and thus a wider allowable bar spacing. When a compressive force is present, the Service-level steel stress is calculated per AASHTO LRFD Eq. C12.11.3-1. Traditional allowable stress formulas are used to calculate the steel stress when a tensile force is present.

Length and bar end location for the k2, k3, m2, and m3 bars for the twin and triple barrel configurations are first determined based on the points where these bars are no longer required to resist flexural forces. The tensile capacity of the continuing reinforcing is then evaluated per AASHTO LRFD Art. 5.8.3.5. If the tensile capacity is insufficient, the cutoff points are shifted towards the walls in increments equaling 2.5% of the cell span until the tensile capacity of the continuing reinforcing is adequate. The bar is then extended past the cutoff point per AASHTO LRFD Art. 5.11.1.2.1. Lastly, the length between the point of maximum moment and the bar end is checked to ensure adequate development length is provided per AASHTO LRFD Art. 5.11.2.1.

The k6 and m6 bars are full width bars with a maximum spacing of 18 in. to satisfy the provisions of AASHTO LRFD Art. 5.10.3.2. To reduce the overall reinforcing weight, the size of the k6 and m6 bars is limited to a #5 or smaller.

The k7 and m7 bars will typically be larger than the k6 and m6 bars, respectively, and thus these bars cannot be terminated in a tension region per the provisions of AASHTO LRFD Art. 5.11.1.2.1. Therefore, length and bar end location for the k7 and m7 bars are determined by extending the bar beyond the inflection point location per AASHTO LRFD Art. 5.11.1.2.3. The length between the point of maximum moment and the bar end is then checked to ensure adequate development length is provided per AASHTO LRFD Art. 5.11.2.1. In shallow fill situations, an inflection point will likely not exist in the slab and the k7 bar will be extended across the full width of the slab.

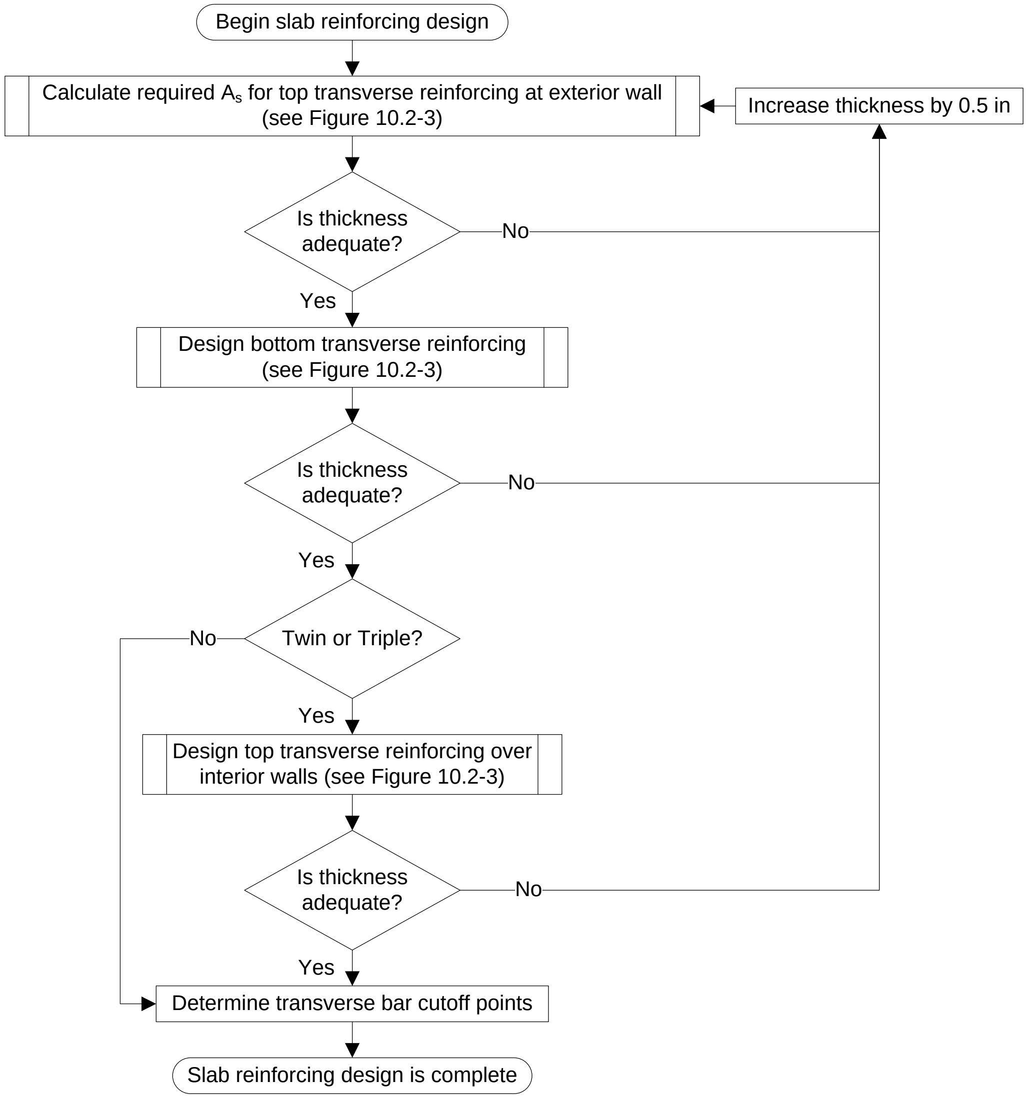


Figure 10.2-1 Slab Design Flowchart

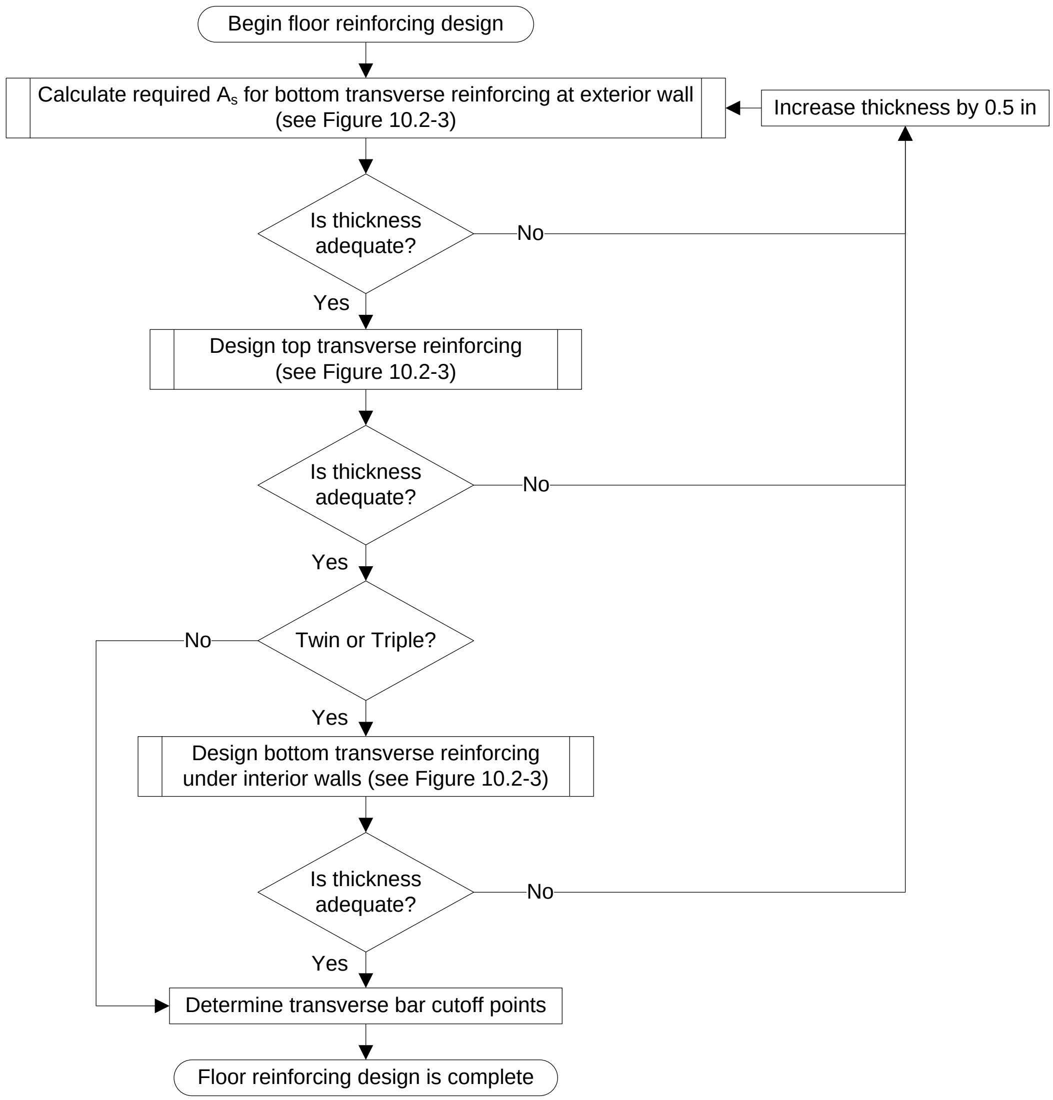


Figure 10.2-2 Floor Design Flowchart

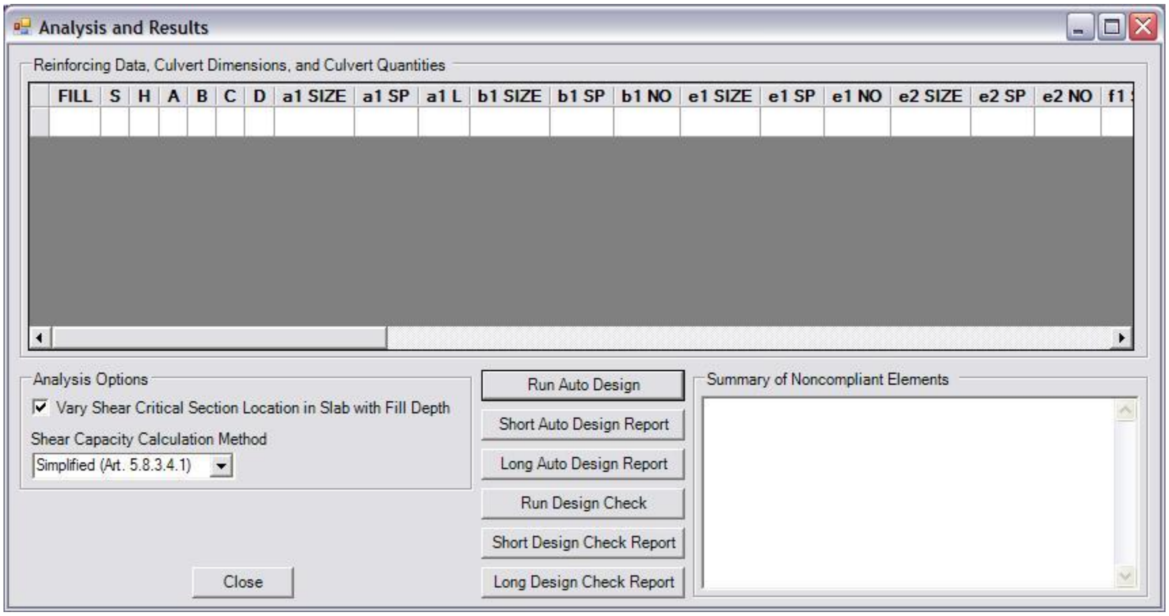


Figure 10.2-3 Analysis and Results Screen

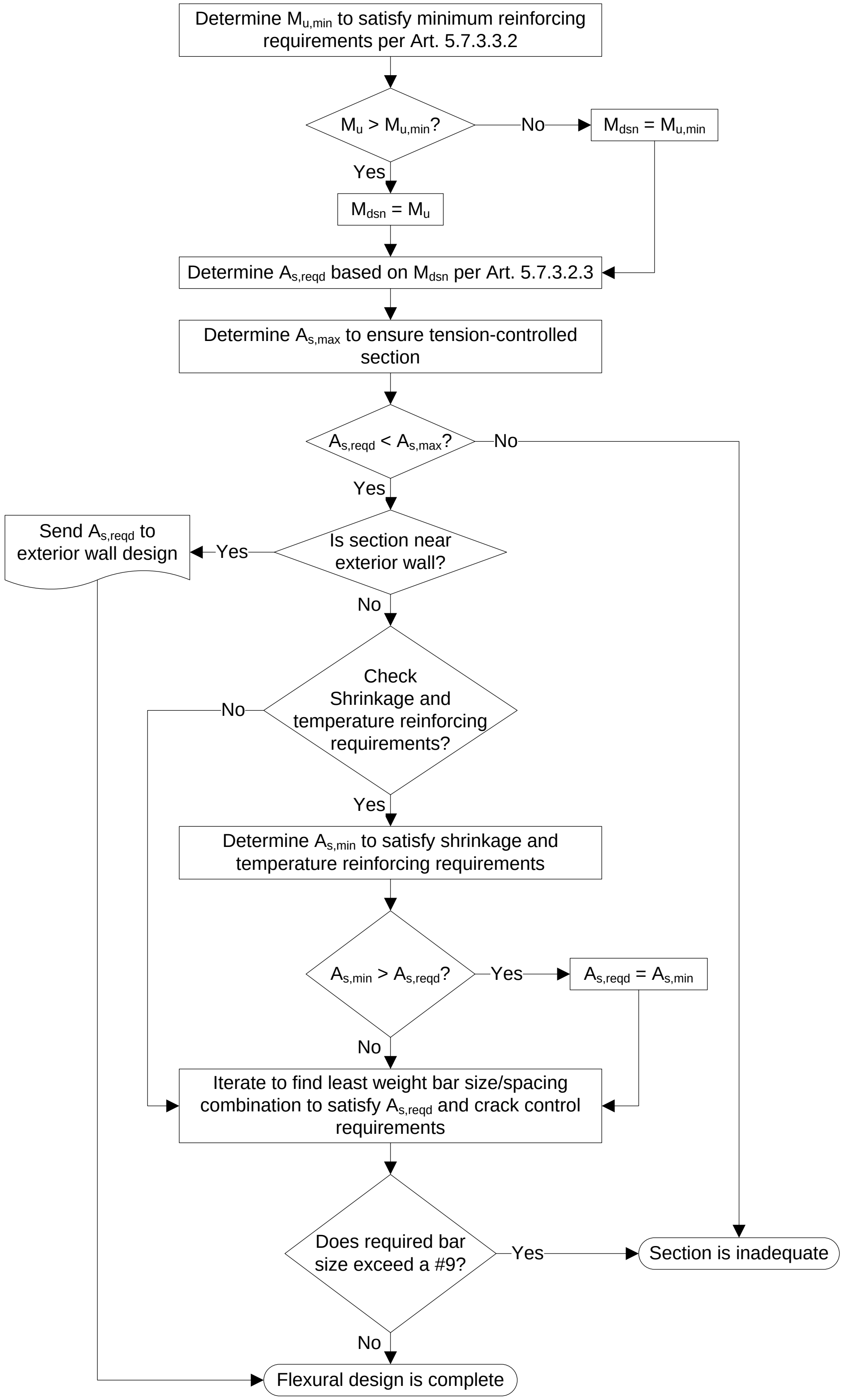


Figure 10.2-4 Flexural Design Flowchart

10.3 Exterior Wall Design

The exterior wall design process is presented in Figure 10.3-1. Three individual wall designs are calculated in order to determine the distribution of reinforcing between the outside and inside faces which results in the least-weight solution. For Design 1 the reinforcing is initially split equally between the outside and inside faces. For Design 2, 66.7% of the reinforcing is initially placed in the outside face and for Design 3, 75% of the reinforcing is initially placed in the outside face. At the end of each wall design the total weight of the vertical exterior wall reinforcing is calculated for a three foot barrel segment. The wall design that results in the least-weight is then selected for the final exterior wall design.

Within each wall design, the required size for the outside face reinforcing bars is determined for 6 in., 9 in., and 12 in. bar spacings. For each spacing, the total weight of the outside face bars is calculated for a three foot barrel segment. The spacing that results in the least-weight is then used for that particular wall design.

Critical section locations for the top and bottom wall designs are based on the provisions of AASHTO LRFD Art. C5.7.3.2.1. The critical section for the mid-height wall design is assumed to occur at the 0.5 point. For the shear capacity checks, the critical section locations are set at a distance d_v beyond the end of the haunch per the provisions of AASHTO LRFD Art. C5.13.3.6.1.

The column design process used for the exterior wall design is presented in Figure 10.3-2. A factored interaction diagram is calculated for the given wall section following the provisions of AASHTO LRFD Art. 5.7.2. Tension-controlled and compression-controlled resistance factors are taken from AASHTO LRFD Art. 5.5.4.2.1.Slenderness effects are assumed to have a negligible effect on the wall design and thus are not accounted for in the exterior wall.

The axial capacity of the section is first checked to ensure the maximum factored axial forces for each Strength-level load case are less than the maximum factored pure compression capacity calculated in accordance to AASHTO LRFD Eq. 5.7.4.4-3. The minimum factored axial forces for each load case are also checked to ensure they exceed the pure tensile capacity of the provided reinforcing.

If the section has adequate axial capacity, the flexural capacity for the section is then evaluated. Since flexural capacity varies with axial load, two factored flexural capacities must be calculated for each Strength-level load case. One factored flexural capacity correlates with the minimum factored axial force from the section force envelope and the other correlates with the maximum factored axial force from the section force envelope. The two factored flexural capacities are compared to the maximum factored moment from the section force envelope. If the maximum factored moment is less than both factored flexural capacities, the section is considered adequate for that load case.

If the section is found to be inadequate, the reinforcing steel is increased and the section is reevaluated. The maximum allowable percentage of reinforcing steel is set at 4% per Iowa DOT OBS office policy. The member thickness is increased and reevaluated when the required reinforcing percentage exceeds 4%.

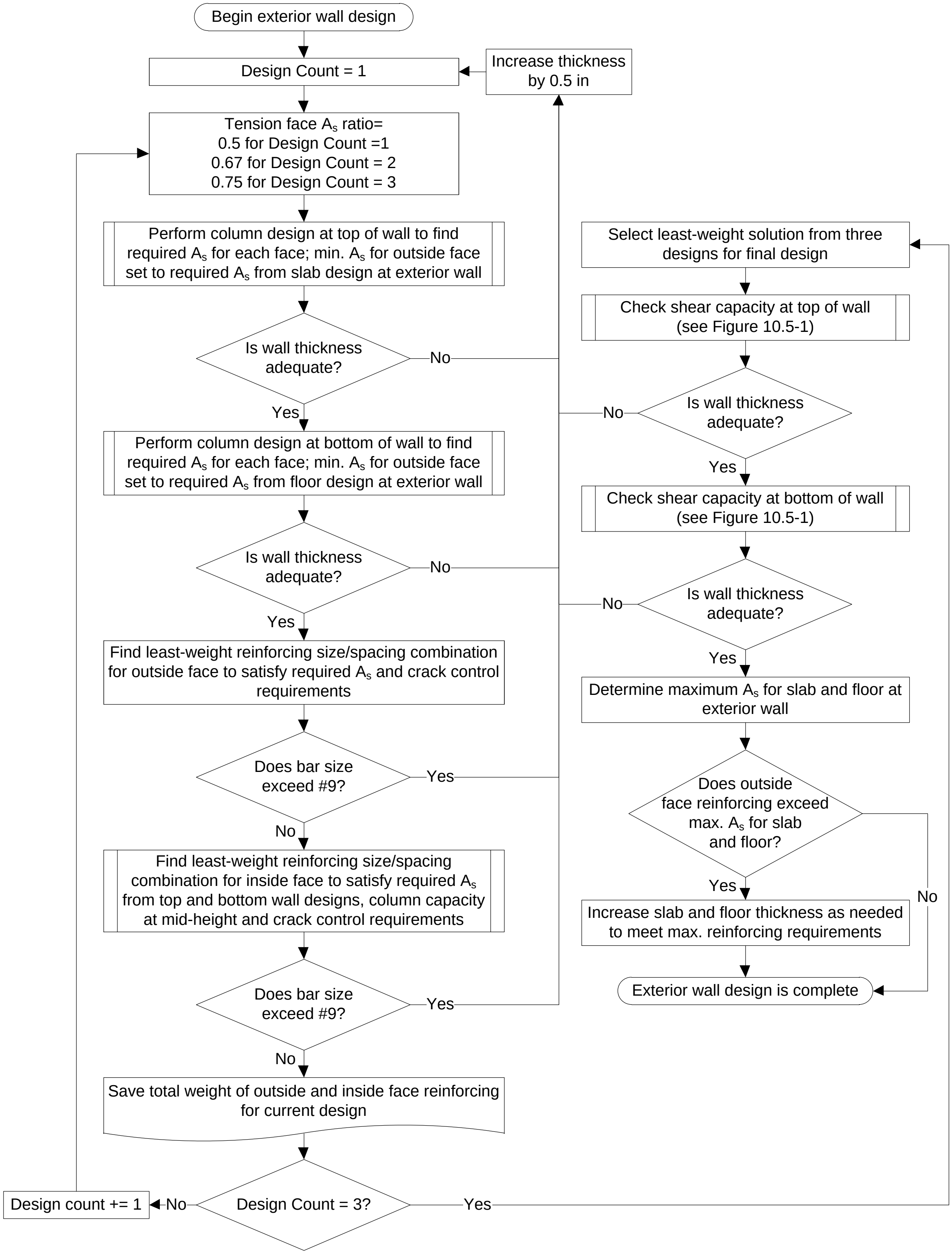


Figure 10.3-1 Exterior Wall Design Flowchart

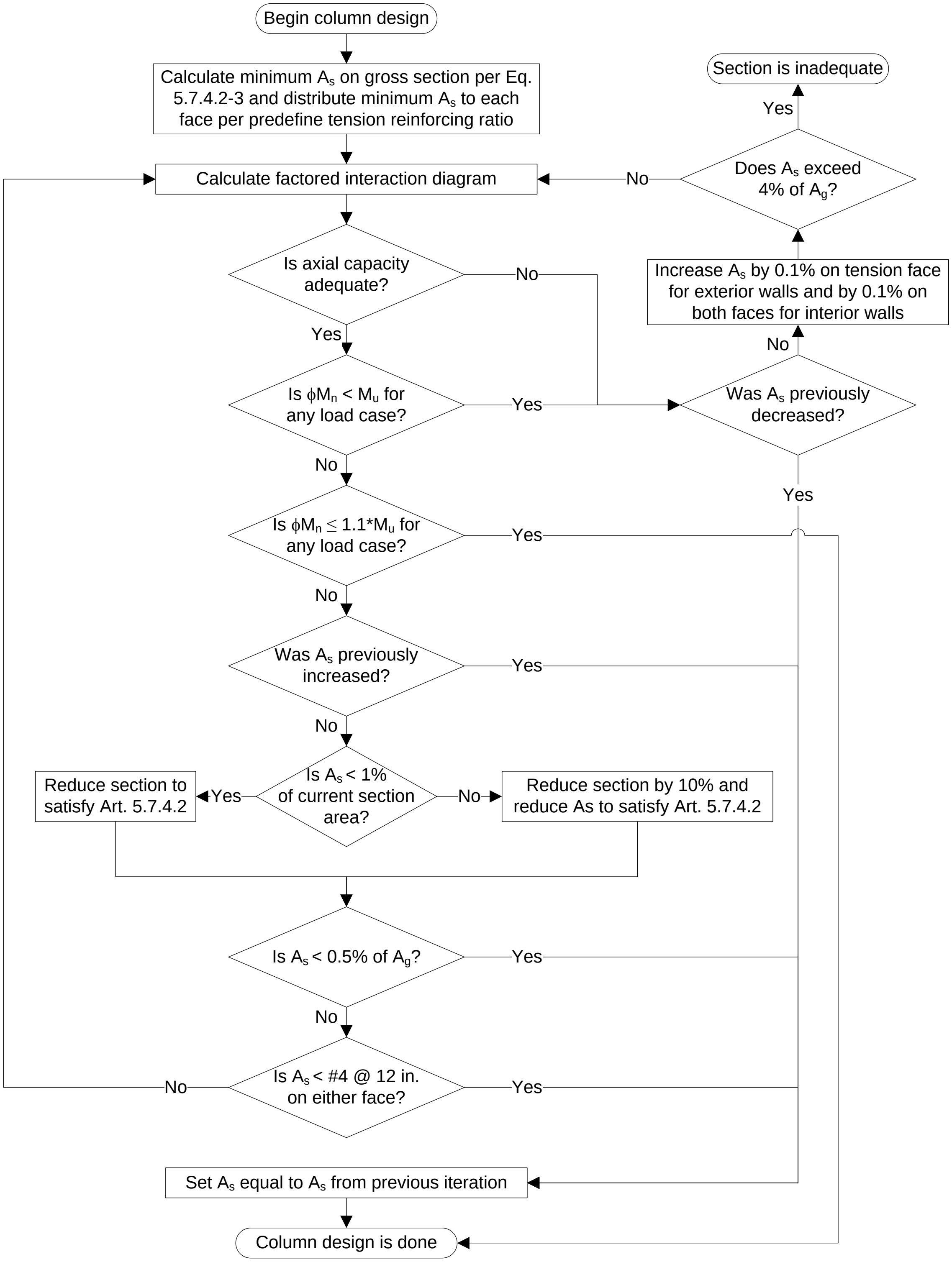


Figure 10.3-2 Column Design Flowchart

If the flexural capacity exceeds 110% of the factored moment for all load cases, the reinforcing will be reduced and the section reanalyzed. The initial reinforcing is set at the minimum required by AASHTO LRFD Eq. 5.7.4.2-3 using the full section dimensions. In order to reduce the reinforcing below the limit set by AASHTO LRFD Eq. 5.7.4.2-3, the section dimensions used for the column analysis must be reduced. The provisions of AASHTO LRFD Art. 5.7.4.2 require the minimum reinforcing on the reduced section satisfy the greater of AASHTO LRFD Eq. 5.7.4.2-3 or 1%. For typical material strengths (4 ksi concrete and Grade 60 reinforcing) the initial reinforcing will be less than 1% of the gross section. Therefore, for the first section reduction, the reinforcing area will not change and the section dimensions will be set so the reinforcing area is 1% of the reduced section. For subsequent section reductions, the section area is reduced by 10% and the reinforcing area reduced to the minimum required by AASHTO LRFD Art. 5.7.4.2. Absolute minimum reinforcing limits are set at 0.5% of the gross section per Iowa DOT OBS office policy or an area that equates to a #4 spaced at 12 in. on either face.

Once the section is found to have adequate flexural and axial capacity, the shear capacity at the top and bottom of the wall is evaluated. The process for calculating the factored shear capacity is presented in Figure 10.5-1. Lastly, since the exterior wall design can increase the area of reinforcing in the slab and floor near the exterior wall, the maximum allowable reinforcing area for the slab and floor is calculated and compared to the provided area. If necessary, the slab and/or floor thickness will be increased to ensure the flexural reinforcing necessary for the exterior wall design will not exceed the maximum allowable area for the slab and floor.

10.4 Interior Wall Design

The interior wall design process is presented in Figure 10.4-1. The same column design process, presented in Figure 10.3-2, used for the exterior wall design is also utilized for the interior wall design with one exception. For the interior wall, the reinforcing is always equally distributed to each face. This equal reinforcing distribution eliminates the need for the multiple designs and leads a design process that is less complex than the exterior wall design process. Additionally, since the interior walls are not subjected to any direct transverse loads, the factored shear force in the walls is insignificant and thus the shear capacity checks have been eliminated from the interior wall design process. Similar to the exterior wall, slenderness effects are assumed to have a negligible effect on the wall design and thus are not accounted for in the interior wall design.

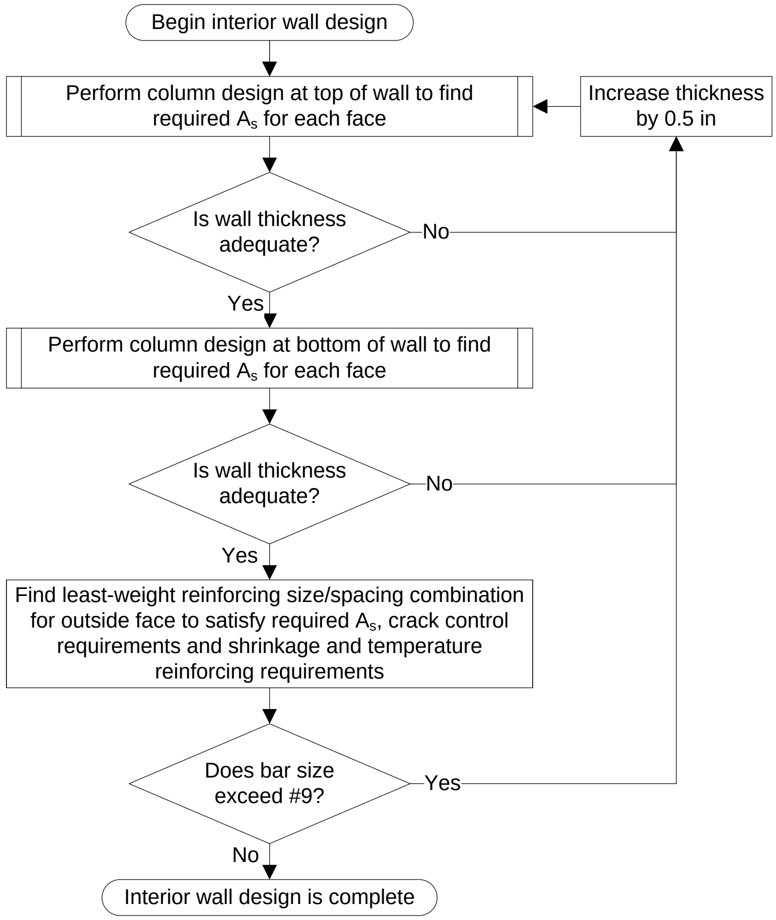


Figure 10.4-1 Interior Wall Design Flowchart

10.5 Slab and Floor Shear Capacity

The process used to calculate the shear capacity of the slab and floor is presented in Figure 10.5-1. The shear capacity calculation method is selected by the user on the *Analysis and Results* screen (Figure 10.2-3). By default, the simplified provisions of AASHTO LRFD Art. 5.8.3.4.1 are utilized. Other options for the shear capacity calculation method include utilizing the MCFT provisions of AASHTO LRFD Art. 5.8.3.4.2 or “Best Result”. “Best Result” calculates the shear capacity per both the simplified and MCFT provisions and sets the member shear capacity equal to the larger value.

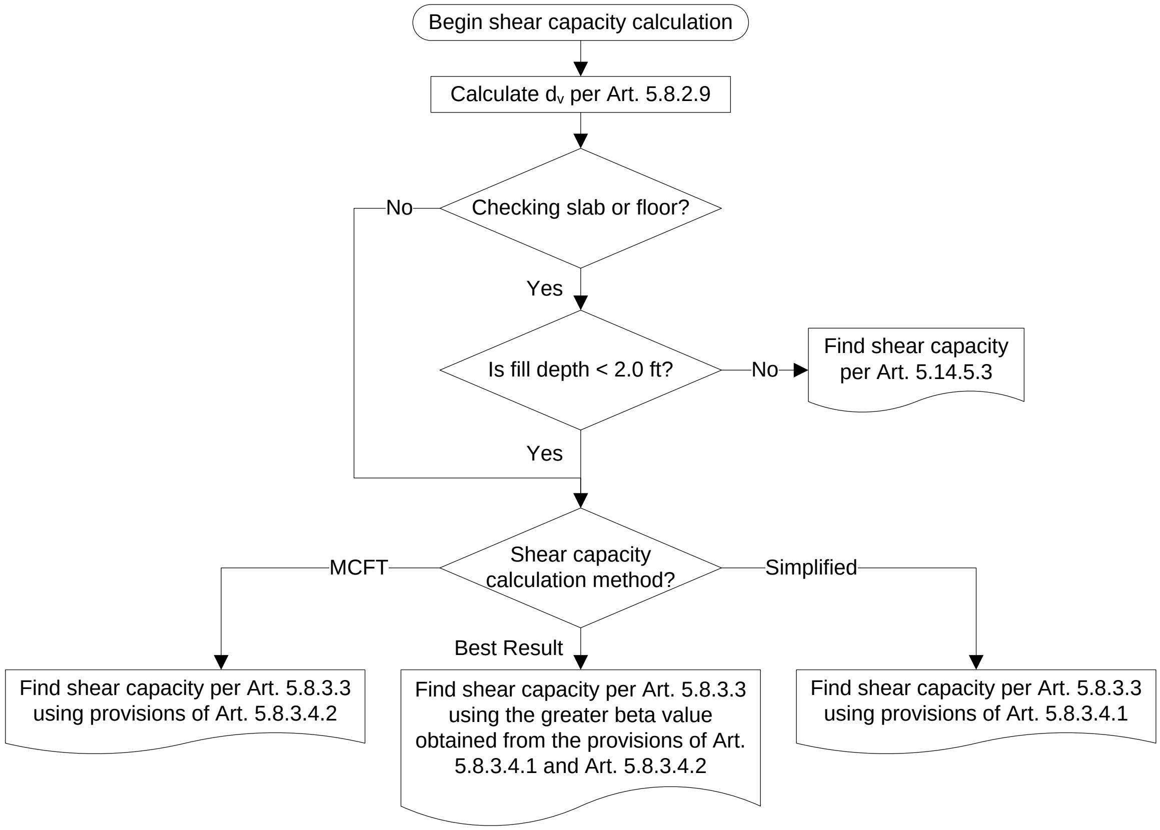


Figure 10.5-1 Shear Capacity Flowchart

Appendix A Input Field Default, Minimum, and Maximum Values

	Input Field	Units	Default Value	Min. Value	Max. Value
Culvert Geometry	Cell Span	ft.	3	3	20
	Cell Height	ft.	3	3	20
	Min. Slab Thickness	in.	8	8	36
	Min. Ext. Wall Thickness	in.	9	8	36
	Min. Int. Wall Thickness	in.	9	8	36
	Min. Floor Thickness	in.	10	8	40
	Max. Slab, Floor and Wall Thickness	in.	36	12	48
	Haunch Length/Width	in.	6	0	12
	Frost Trough Height	in.	4	0	12
	Width of Constant Depth Portion of Frost Trough	in.	4	0	6
	Width of Tapered Portion of Frost Trough	in.	6	0	6
	Floor Extension Beyond Outside Face of Exterior Wall	in.	3	0	9
	Integral Wearing Surface Thickness	in.	0	0	3
	Mud Mat Thickness	in.	2	0	3
Fill Properties	Fill Height	ft.	0	0	100
	Min. Fill Height	ft.	0	0	99
	Max. Fill Height	ft.	55	1	100
	Fill Height Increment	ft.	2	0.25	5
	Soil-Structure Interaction Factor	--	1	0	5
	Water Height Above Bottom of Slab	ft.	0	0	100
	Pavement Thickness	in.	10	0	24
Live Load	Enter Fill Interaction Factor	--	0	0	5
	Tire Patch Length	in.	10	0	50
	Tire Patch Width	in.	20	0	50
	Equivalent Height of Soil	ft.	2	0	10
	Max. Percentage of Live Load	%	33	0	100
	Neglect for Fill Depths Greater Than	ft.	8	0.1	100
	Live Load Step Distance (Max.)	in.	24	1	30
	Axle Spacing Increment	ft.	4	1	8
Materials	Concrete Unit Weight	kcf	0.15	0	1
	Concrete Compressive Strength	ksi	4	1	20
	Concrete Max. Aggregate Size	in.	0.75	0.25	2
	Reinforcing Steel Yield Strength	ksi	60	10	100
	Soil Unit Weight	kcf	0.12	0	1
	Effective Friction Angle	deg	30	0	89
	Water Unit Weight	kcf	0.0624	0	1
	Pavement Unit Weight	kcf	0.15	0	1

(Table continued on next page)

	Input Field	Units	Default Value	Min. Value	Max. Value
Concrete Cover Dim.	Edge Clearance - Typical	in.	2	1	4
	Edge Clearance - Top of Slab	in.	2	1	4
	Edge Clearance - Top of Floor	in.	2.25	1	4
	Edge Clearance - Bottom of Floor	in.	3.5	1	4
	End Clearance - Vertical Bar - Top	in.	2	1	4
	End Clearance - Vertical Bar - Bottom (Min.)	in.	3	1	4
	End Clearance - Transverse Bar	in.	2	1	4
Load Factors, Load Modifiers and Exposure Factors	Strength I - Load Factor - DC (Max.)	--	1.25	0	10
	Strength I - Load Factor - DC (Min.)	--	0.9	0	10
	Strength I - Load Factor - DW (Max.)	--	1.5	0	10
	Strength I - Load Factor - DW (Min.)	--	0.65	0	10
	Strength I - Load Factor - EH (Max.)	--	1.35	0	10
	Strength I - Load Factor - EH (Min.)	--	1	0	10
	Strength I - Load Factor - EV (Max.)	--	1.3	0	10
	Strength I - Load Factor - EV (Min.)	--	0.9	0	10
	Strength I - Load Factor - LL + IM	--	1.75	0	10
	Strength I - Load Factor - LS	--	1.75	0	10
	Strength I - Load Factor - WA	--	1	0	10
	Strength I - Load Modifier - DC (Max.)	--	1	0	10
	Strength I - Load Modifier - DC (Min.)	--	1	0	10
	Strength I - Load Modifier - DW (Max.)	--	1	0	10
	Strength I - Load Modifier - DW (Min.)	--	1	0	10
	Strength I - Load Modifier - EH (Max.)	--	1.05	0	10
	Strength I - Load Modifier - EH (Min.)	--	1	0	10
	Strength I - Load Modifier - EV (Max.)	--	1.05	0	10
	Strength I - Load Modifier - EV (Min.)	--	1	0	10
	Strength I - Load Modifier - LL + IM	--	1	0	10
	Strength I - Load Modifier - LS	--	1	0	10
	Strength I - Load Modifier - WA	--	1	0	10

(Table continued on next page)

	Input Field	Units	Default Value	Min. Value	Max. Value
Load Factors, Load Modifiers and Exposure Factors	Strength II - Load Factor - DC (Max.)	--	1.25	0	10
	Strength II - Load Factor - DC (Min.)	--	0.9	0	10
	Strength II - Load Factor - DW (Max.)	--	1.5	0	10
	Strength II - Load Factor - DW (Min.)	--	0.65	0	10
	Strength II - Load Factor - EH (Max.)	--	1.35	0	10
	Strength II - Load Factor - EH (Min.)	--	1	0	10
	Strength II - Load Factor - EV (Max.)	--	1.3	0	10
	Strength II - Load Factor - EV (Min.)	--	0.9	0	10
	Strength II - Load Factor - LL + IIM	--	1.35	0	10
	Strength II - Load Factor - LS	--	1.35	0	10
	Strength II - Load Factor - WA	--	1	0	10
	Strength II - Load Modifier - DC (Max.)	--	1	0	10
	Strength II - Load Modifier - DC (Min.)	--	1	0	10
	Strength II - Load Modifier - DW (Max.)	--	1	0	10
	Strength II - Load Modifier - DW (Min.)	--	1	0	10
	Strength II - Load Modifier - EH (Max.)	--	1.05	0	10
	Strength II - Load Modifier - EH (Min.)	--	1	0	10
	Strength II - Load Modifier - EV (Max.)	--	1.05	0	10
	Strength II - Load Modifier - EV (Min.)	--	1	0	10
	Strength II - Load Modifier - LL + IIM	--	1	0	10
	Strength II - Load Modifier - LS	--	1	0	10
	Strength II - Load Modifier - WA	--	1	0	10
	Service I - Load Factor - DC	--	1	0	10
	Service I - Load Factor - DW	--	1	0	10
	Service I - Load Factor - EH	--	1	0	10
	Service I - Load Factor - EV	--	1	0	10
	Service I - Load Factor - LL + IM	--	1	0	10
	Service I - Load Factor - LS	--	1	0	10
	Service I - Load Factor - WA	--	1	0	10
	Service I - Exposure Factor - Slab	--	1	0.1	1
	Service I - Exposure Factor - Walls	--	1	0.1	1
	Service I - Exposure Factor - Floor	--	1	0.1	1